

THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING IN MACHINE AND
VEHICLE SYSTEMS

Forecasting Indian Road Traffic Casualties: Guidance to Prioritise Road Safety
Technologies and Regulations

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ABSTRACT

Introduction: India accounts for 11% (nearly 150,000) of global road traffic deaths and its fatality rate is 22.6 per 100,000 people, almost three times higher than that of the European region. India is committed to reducing fatalities and has signed the Stockholm declaration to halve the fatalities by 2030. Fatality reduction can be achieved through various countermeasures. To prioritise between various countermeasures, it is important to understand future road safety challenges and to predict the effectiveness of these countermeasures, e.g. the impact of pre-crash safety technologies and recently implemented vehicle safety regulations. **Methods:** Firstly, the effectiveness of state-of-the-art pre-crash safety technologies for different road users in India was investigated using simple deterministic rules; one optimistic and one conservative rule for each safety technology, to identify future safety gaps. Secondly, the effectiveness of recently implemented vehicle safety regulations was estimated and used to characterise remaining crash. Since both these studies found that the proportion of crashes involving Powered Two-Wheelers (PTWs) will remain high, the final study identified the most frequent crash configurations of PTWs. **Results:** Autonomous Emergency Braking (AEB) and Electronic Stability Control (ESC) in cars, trucks, and buses were found to be the most effective pre-crash safety technologies among the evaluated pre-crash safety systems for reducing injury crashes in India. While these technologies will help reduce future crashes, the proportion of heavy vehicle-to-pedestrian and heavy vehicle-to-PTW crashes will increase. The recently implemented regulations were estimated to reduce 6–13% of road traffic fatalities in India. Overspeed alerts, offset frontal crash performance by standardised testing and seatbelt reminders were found to be the three components of the regulations most effective at reducing fatalities when the optimistic rules were used. Both these studies illustrate that a large proportion of the very frequent crashes involving PTWs will remain. The most frequent crash configurations involving PTWs in India were front-to-front PTW to truck or car, followed by riders falling of the PTW (ground impact). **Conclusions:** Although the recently implemented vehicle safety regulations in India will contribute to a substantial fatality reduction, they alone will not achieve the reduction target set for 2030. Estimates of the remaining future crashes call for increased attention to fatal crashes involving PTW riders and pedestrians. To address the safety of PTW users, one recommendation is to focus on in-crash protection of PTW users, in addition to strong enforcement of the helmet law and other existing regulations.

Keywords: Accidents, ADAS, assessment, safety benefit, crash, effectiveness, evaluation, future crashes, vision zero

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LIST OF APPENDED PAPERS

Paper I

Puthan P, Lubbe N, Davidsson J. Counterfactual Simulation of Pre-crash Vehicle Safety Technologies on Indian Crash Data to Predict Future Road Traffic Impact types and Pre-crash events.
(Ready for submission)

Author's contributions:

Puthan and Lubbe designed the study. Puthan carried out the analysis. The paper was written by Puthan under the supervision of Lubbe and Davidsson, who also reviewed the paper.

Paper II

Puthan P, Lubbe N, Davidsson J. Estimated Lives Saved by Recently Implemented Vehicle Safety Standards in India: Implications and Future Safety Needs.
(Submitted to IRCOB, addressing reviewer comments)

Author's contributions:

Puthan and Lubbe designed the study. Puthan analysed the data and wrote the paper. The paper was written by Puthan under the supervision of Lubbe and Davidsson, who also reviewed the paper.

Paper III

Puthan P, Lubbe N, Shaikh J, Sui B, Davidsson J. Defining crash configurations for Powered Two-Wheelers: Comparing ISO 13232 to recent in-depth crash data from Germany, India, and China. *Accid. Anal. Prev.* 2021;151(19):105957. <https://doi.org/10.1016/j.aap.2020.105957>

Author's contributions:

Puthan and Lubbe designed the study. Puthan analysed the Indian data and performed the analysis when data were merged with descriptive statistics from Germany and China. Shaikh provided the statistics from Germany and Sui provided the statistics from China. The paper was written by Puthan under the supervision of Lubbe and Davidsson, who also reviewed the paper.

Table of Contents

ABSTRACT	III
ACKNOWLEDGEMENTS	V
LIST OF APPENDED PAPERS	VII
Paper I.....	VII
Paper II	VII
Paper III.....	VII
1. INTRODUCTION:	1
1.1 Road Safety in India.....	1
1.2 Theoretical background.....	2
1.2.1 Injury reduction strategies	2
1.2.2 Methods for forecasting the impact of interventions on traffic safety.....	4
1.3 Policy interventions in road safety management.....	4
1.3.1 Interventions in the USA and Europe.....	4
1.4 India's Interventions in India.....	6
1.5 Objective.....	7
2. SUMMARY OF PAPERS.....	9
3. GENERAL DISCUSSION	17
3.1 Scope.....	17
3.2 Effectiveness assessment	18
3.3 Result implications	19
3.4 Road safety in India and sustainable development	20
3.5 Limitations	21
3.6. Future Work.....	22
4. CONCLUSIONS.....	23
BIBLIOGRAPHY	25

1. INTRODUCTION

Efficient transportation via road, rail, and air is vital for a country's economic development. Having a vast network of roads enables the movement of goods and people, but at the same time, also increases the risk of casualties. Globally, 1.35 million people lose their lives and nearly 50 million people are injured in road crashes every year (World Health Organization, 2018). Road traffic crashes are the eighth leading cause of death and disability. Further, road traffic deaths are disproportionately high in low- and middle-income countries.

The current road traffic situation in low- and middle-income countries cannot be compared to the situation in high-income countries, either currently or in the past, because low- and middle-income countries differ in terms of composition, proportion of road users, level of safety of the vehicles, infrastructure design, road users' risk-taking attitude, user acceptance of vehicle safety technologies, and timely access to emergency care. For instance, many South and Southeast Asian countries have a higher proportion of powered two-wheelers (PTWs) than high-income countries. While efforts to reduce traffic fatalities have been made worldwide, drastic differences in achieved results can be observed among countries. According to the World Health Organization (2018) report, reductions were achieved in 48 middle- and high-income countries, while fatalities increased in 87 low- and middle-income countries. The report states that no low-income country has managed to reduce road traffic fatality rates since 2013 (World Health Organization, 2018).

High-income countries have achieved a steady decline in road crash fatalities over the past few decades (European Commission, 2018; Evans, 2014). The fatality rates per 100,000 people were the lowest (9.3) in Europe, while 22.6 in India (World Health Organization, 2018). Unfortunately, the best practices successfully adopted by high-income countries can probably not be copied directly, because of the different situations in different countries: local conditions may vary and regional factors need to be considered for the safety action plans (Wegman, 2017). Hence, additional research is required to provide best practices in infrastructure design and regulations for low- and middle-income countries. This thesis is focusing on research for the reduction of road traffic casualties in India.

1.1 Road Safety in India

According to World Health Organization estimates, India accounts for 11% of global road traffic deaths, which amounted to 299,091 deaths in 2016 (World Health Organization, 2018). The estimate is almost double the nationally reported figure of 150,785 fatalities (Transport Research Wing, 2020). The World Health Organization estimate is close to the 2017 estimate made by the research program Global Burden of Disease Study of nearly 218,900 fatalities. These differences in estimates imply that it is difficult to know the true numbers, and the nationally reported figure is an under-estimate (Bhalla et al., 2017; Dandona et al., 2008; Singh et al., 2018) which pose limitations on the research. In addition to the suffering, these casualties

introduced, the cost of road traffic injuries in India is very high. It has been estimated that these are nearly 3.5% of India's Gross Domestic Product (World Bank, 2018).

India has experienced several years of economic growth, but road infrastructure has not been sufficient to meet the demand for created by increasing numbers of vehicles on the roads (Gururaj and Gautham, 2017; PTI, 2016). Meanwhile, the country's population, and the number of road vehicles are increasing rapidly (Figure 1) (Transport Research Wing, 2020).

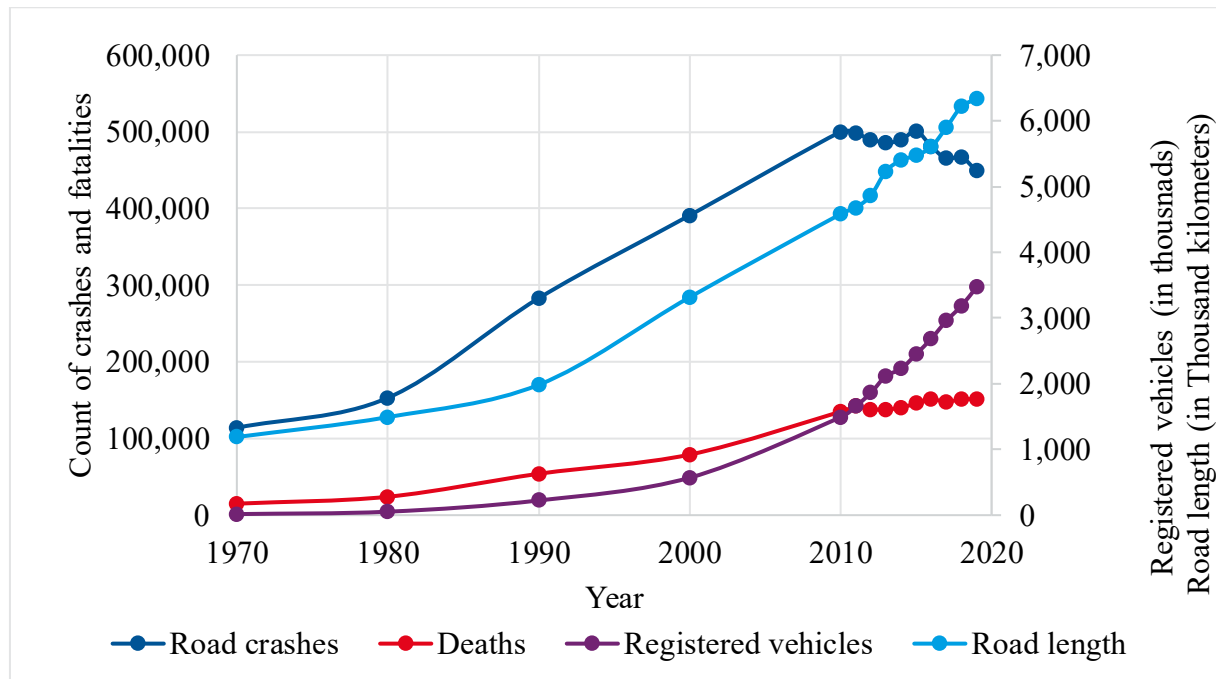


Figure 1. Trends in road crashes, deaths, registered vehicles, and road length in India over the last 50 years

India could not meet the commitment towards Brasilia declaration and SDG3.6, that is, to halve the road traffic fatalities by 2020. While the introduction of multiple road safety interventions has resulted in a lower rate of increase in road fatalities, India still suffer from increasing road fatalities (Mohan et al., 2021). At the third ministerial conference on road safety, India signed the Stockholm declaration to halve the number of fatalities in 2020 by 2030 (Stockholm Declaration, 2020). It is evident that unless concrete actions are taken through enforcement, education, and various policies this commitment will not be met (Mohan et al., 2021).

A country's road safety developments are closely connected to its economic development (Yannis et al., 2014). India is in an early phase of motorisation; when the economy grows, it is expected that safer infrastructure, safer vehicles, and new road safety strategies will lead to reductions in road traffic fatalities and injuries.

1.2 Theoretical background

1.2.1 Injury reduction strategies

Road safety is a multifaceted concept: road users (drivers and occupants of motorised vehicles, bicyclists, PTW users, and pedestrians), road infrastructure, and vehicles each play an integral

part. In road safety, the principle is to control the harm to humans by various countermeasures just like any other critical situation, like an earthquake or volcanic eruption. From 1950 to 1970, researchers predominantly looked into the cause or incident that led to a crash (Hagenzieker et al., 2014). In 1973, William Haddon (1973) proposed ten strategies to control harm or avoid damage, which can be applied to a variety of undesirable incidents caused by a large, rapid transfer of energy. These strategies, intended to eliminate, regulate, modify, or mitigate the harmful impact, were later adapted to traffic safety (Haddon, 1973). Haddon conceptualised these injury control strategies specifically to road crashes by separating these strategies into phases and components of the system (Table 1) (Haddon, 1980). Three distinct phases of the crash (pre-crash, crash, and post-crash) and three different components of the system they are related to (user, vehicle, or infrastructure) were identified.

Table 1. Haddon's Matrix, adapted from (ITF, 2008)

Phase	User (host)	Vehicle (Agent)	Infrastructure (Environment)
Pre-crash (crash prevention)	Attitudes Education Information Impairment Enforcement	Braking (Anti-lock brakes) Handling (Stability control) Roadworthiness Speed Management	Speed limits Pedestrian facilities Road design and layout
Crash (injury prevention)	Use of protective Equipment (Helmets)	Other safety devices Protective equipment Crash protective design	Median barriers Crash protective roadside objects
Post-crash (life-sustaining)	First-aid skills Access to medics	Fire risk Ease of access	Congestion Rescue facilities

While Haddon's three-by-three matrix helps to define injury control strategies in an organised manner, the presentation failed overlooked to present the transition or connection between phases. This issue has been addressed by the design of the integrated safety chain (Figure 2).

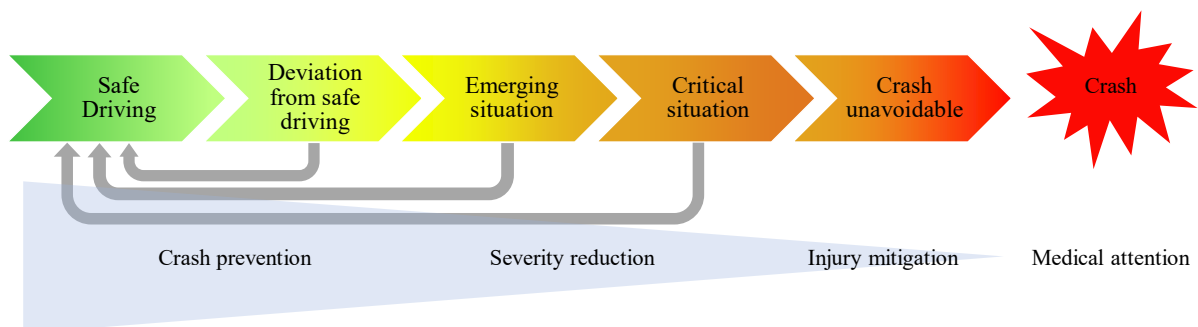


Figure 2. Integrated safety chain, adapted from (Lie, 2012)

As illustrated in Figure 2, a crash can be characterised as a chain of events over time, from safe driving until a crash occurs. Depending on the phases, various countermeasures can be taken either to prevent the crash or mitigate its severity. For instance, a distracted driver can be brought back into the safe driving phase with a warning when all factors are still under control.

Similarly, Lane Departure Warning nudge drivers back to safe driving from an emerging situation (caused by drifting outside the driving lane). Another system, Electronic Stability Control (ESC), helps the driver regain control in a critical situation. Once the crash is unavoidable, in-crash systems facilitate injury mitigation. This integrated safety chain approach proceeding the crash shows when there is an opportunity to return to normal driving with the help of countermeasures.

1.2.2 Methods for forecasting the impact of interventions on traffic safety

Forecasting the effectiveness of interventions is crucial in order to plan and prioritize future road safety policies. However, there are few methods available for evaluating the future impact of various road safety interventions. One method uses in-depth crash databases to estimate the potential reduction in crashes and casualties of vehicle safety technologies. Rizzi et al. used in-depth crash data from Sweden to estimate the potential benefit of Anti-lock Braking System (ABS) in PTWs (Rizzi et al., 2015). Similar research was carried out for other regions as well, using the information from in-depth crash data (Lich et al., 2015; Puthan et al., 2018; Teoh, 2013).

More recently, Strandroth developed another method to estimate the future impact of vehicle safety interventions in Sweden, and then analysed the remaining crashes to identify important future safety gaps in interventions (Strandroth et al., 2012). This method was validated by applying simulated interventions to past crash data, when the results of the interventions were already known (Strandroth, 2015). The new method was utilised to predict future crashes in Sweden, in order to identify safety needs for the 15 years following 2014, the date of the baseline data (Strandroth et al., 2016). The prediction of future needs in Sweden was achieved in three steps: 1. Analyse the effect of future traffic volume increases and estimate the crash exposure; 2. Introduce assumptions regarding the influence of various planned safety interventions on road safety; and 3. Define target crashes and apply risk reduction factors for each countermeasure. For Sweden, Strandroth et al. found that the safety of car occupants will continue to increase, become safer while additional efforts are required to reduce pedestrian and cyclist injuries.

Similarly, in this thesis, safety interventions are modelled using simple deterministic rules to predict the effectiveness of individual intervention and combined effectiveness of interventions; the remaining crashes are analysed.

1.3 Policy interventions in road safety management

1.3.1 Interventions in the USA and Europe

Several high-income countries have shown that significant road traffic casualty reductions are achievable. These reductions were achieved through various strategies, depending on each country's needs. For instance, in 1970 the USA empowered a national lead agency for road safety, the National Highway Traffic Safety Administration (NHTSA), with the mission to save lives, prevent injuries, and reduce vehicle-related crashes in the USA (Kahane, 2015). NHTSA was responsible for creating vehicle safety standards and enforcing them, in partnerships with state and local governments. In addition, NHTSA also created (and maintains) crash databases

that are being used to understand crash patterns and facilitate other crash research activities. In the late 1980s, a comprehensive vehicle test program and the New Car Assessment Program (NCAP) was launched by Insurance Institute of Highway Safety and NHTSA, respectively, to encourage the manufacturing of safer vehicles.

Similar activities were also initiated in Europe: European Union (EU) established the European Enhanced Vehicle-safety Committee (EEVC) and member states organised the Euro NCAP to promote safer vehicles. These activities have led to a reduction of fatalities of car, bus and truck occupants as well as bicyclists and pedestrians in Europe (Strandroth et al., 2014; Van Ratingen et al., 2016). United Nations formed programs under the United Nations Economic Commission for Europe (UNECE) with the intention to promote and harmonise vehicle regulations worldwide. Central agencies responsible for the implementation of changes to promote road safety have played a key role in the reduction of crashes and casualties in high-income countries. Most of these changes, and the decisions that made these changes come alive, were data-driven. Research supported the interventions and the prioritisation of the safety interventions according to the needs of specific countries.

In addition to the initiatives at EU-level, Sweden took a holistic and somewhat different approach towards road safety in the 1990s when their parliament approved a strategic long-term plan to eliminate all road traffic fatalities and serious injuries. This plan, called Vision Zero (Kristianssen et al., 2018), embodies the ethical viewpoint that no one should be seriously injured or killed in road traffic crashes. Vision Zero emphasises shared responsibility between policymakers and road users. Vision Zero also considers humans' tolerance to external forces, more specifically biomechanical properties, while designing or planning interventions.

There has been a continuously steeper decline in road traffic fatalities in Sweden since the implementation of Vision Zero. Seeing the success in Sweden, many other countries have adopted Vision Zero, including the USA, Norway, Denmark, Australia, and New Zealand.

The traditional road safety approach treats road crashes as inevitable and that these are only eliminated when all road users behave perfectly; the road users need to comply and thereby avoid crashes (Hauer, 2020). The Vision Zero approach, in contrast, upholds the principle that road crashes are preventable—and that humans can make mistakes or fail while they are involved in transportation. Rather than delegating the responsibilities associated with safe transportation to the individuals, Vision Zero implemented a safe traffic model that holds designers and policymakers responsible for making safe road systems. To control the kinetic forces beyond the level of human tolerance which can occur during a crash, safer vehicles, safer speeds, and safer roads are vital (figure 3) (Larsson and Tingvall, 2013; Tingvall et al., 2010).

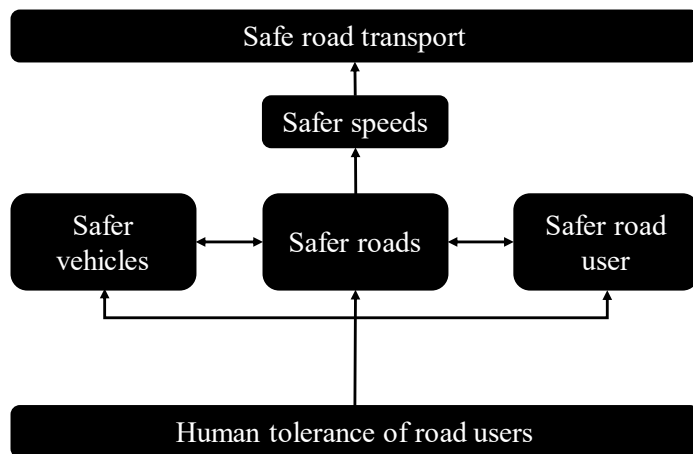


Figure 3. Safe traffic model of the Vision Zero - adapted from (Tingvall et al., 2010)

1.4 Interventions in India

Unfortunately, the situation has not been the same in India as in the USA or in Europe. Until recently, several sectors in the administration in India were responsible for road safety and these activities were not well coordinated. One reason for the lack of a central road safety administration, such as NHTSA, and lack of coordination was the lack of a lead agency in India.

However, in the last decade, India has shown its commitment towards improving road safety by signing the Brasilia and Stockholm declarations. India also recently started implementing additional vehicle safety standards. The Ministry of Road Transport and Highways (MoRTH) formed an expert committee (Sundar Committee, 2007) empowered to: assess the impact of road traffic crashes and casualties, study and learn from best practices in road safety management internationally, to suggest amendment of relevant traffic laws, to suggest measures for rescue and relief of accident victims, and establish a national lead agency at the central government level to propose necessary amendments in traffic laws. After extensive studies, the Sundar committee made several key observations and some of them were:

- Currently, there is no central agency capable of dealing with the increasing road traffic
- Key ministries and public sector agencies play a peripheral role in improving road safety
- Road safety is not a priority in the development agenda of the state and central governments
- The existing National Road Safety Council does not have adequate statutory backing, budgetary resources, or support to be effective

India can learn from the advancements made globally in road safety techniques and safety interventions in order to fast-track its progress on road safety. Based on the review of international best practices, the committee noted that in all studied countries a strong political commitment to promote safety was present. Political will, however, to a large extent was lacking in India (Gururaj, 2014; Tiwari and Mohan, 2018). The committee also noted that a successful national road safety agency, like NHTSA, should be empowered with a fair amount

of authority and adequate financial support to successfully plan and implement various road safety strategies in India. The committee proposed the establishment of the “State Road Safety and Traffic Management Board”, with legislative powers and financial backing from the central government.

The Indian government has mandated several vehicle safety standards during the last five years. The regulations for PTWs include a combined braking system (CBS) for PTWs under 125 cm³ and ABS for PTWs over 125 cm³. The regulations for cars include seat belt reminders, ABS, frontal airbags, reverse parking sensors, front and side crash tests, and pedestrian protection.

India has a federal system in which the central and state governments share the responsibility for implementing laws and amendments approved by the parliamentary house and the president. In 2019, the central government approved a new road safety bill which is an amendment to the existing Central Motor Vehicle Act. The new bill is expected to extensively reform the act, which has not been amended since its creation in 1988. The reforms include an increase in penalties for violating laws and changes in licensing, among various other changes. However, state governments implemented reforms with some modifications. For instance, many state governments decreased the higher penalties by 50% (PWc, 2019). The central government has recently announced its approval of the National Road Safety Board, which is expected to be the national lead agency.

There have also been non-state funded road safety initiatives in India. The Global New Car Assessment Program (NCAP) launched a project called “Safer cars for India”, testing crashworthiness and occupant protection and assigned the tested vehicles providing a star rating (Global NCAP, 2018). As a result, over the years, newer car models have provided improved protection. This initiative helped to raise awareness about safety of cars in the public. However, despite the introduction of safer cars, the road fatalities are not expected drop significantly as nearly 54% of all road fatalities in India are collisions involving pedestrians and PTW users (Transport Research Wing, 2020) and the project did not address the safety for these road users. There have not been many initiatives for PTW and pedestrians.

Although the government has mandated several vehicle safety regulations and amendments to existing rules, there is a lack of scientific evidence-based decisions indicating why these specific modifications have been prioritised. Furthermore, the impact of these changes in India has not yet quantified.

1.5 Objective

Road safety is a public health issue in India. Additional efforts are required to meet the Stockholm deceleration target of halving the fatalities by 50% by 2030 (Mohan et al., 2021).

The overall objective of this licentiate thesis is to forecast Indian road traffic casualties 15 to 20 years from now, to prioritise some guidance of future vehicle safety technologies and road safety regulations.

The specific objectives are:

- to identify the future safety gap when multiple pre-crash safety technologies are present in most of the Indian vehicle fleet. The findings of this study will help determine whether these pre-crash safety technologies can solve the majority of crashes or any additional countermeasures are required;
- to quantify the lifesaving potential of recently implemented vehicle safety standards. The study identifies crashes that will continue to result in fatalities, serving as a guide for additional road safety strategies required to ensure a 50% reduction in fatalities by 2030;
- to estimate the crash configurations that lead to the most severe injuries and fatalities in India and suggest new regulations to address these configurations.

The effectiveness of technologies and vehicle safety regulations was estimated using simple deterministic modelling, applied on retrospective crash data. Therefore, the future steps are:

- to validate the simple modelling technique, which assumes that the technologies would perform in India as they perform in high-income countries, using detailed simulation for at least one technology;
- to estimate the effectiveness of broad infrastructure improvement in India;
- to draw conclusions about the long-term impact of these various countermeasures on the Indian vehicle fleet, considering societal changes and shifts in travel modes, through the analysis of multiple scenarios.

2. SUMMARY OF PAPERS

Paper I: Counterfactual Simulation of Pre-crash Vehicle Safety Technologies Using Indian Crash Data to Predict Future Road Traffic Impact Types and Pre-crash Events

Introduction

Several pre-crash safety technologies have shown their effectiveness in high-income countries. Unfortunately, India's national statistics on road traffic crashes indicate a steady increase in casualties. It is unclear how the proven pre-crash safety technologies will perform in India and what their impact will be on remaining crashes in the future. In this paper, 22 pre-crash safety technologies were considered.

Aim

To characterise the remaining crashes resulting in moderate or worse injuries (Maximum Abbreviated Injury Scale 2+: MAIS2+) when the 22 pre-crash safety technologies are available in most passenger cars, heavy vehicles (buses and trucks), and PTWs.

Method

Two deterministic rules (one optimistic and one conservative) were modelled for each of the 22 pre-crash safety technologies and applied these rules to crash data with MAIS2+ injuries from the Road Accident Sampling System India (RASSI) database. Each rule, tailored to the functionality of each technology, was used to estimate whether the technology would have avoided the crashes in the database. In addition to the effectiveness of each technology alone, the combined effectiveness of all 22 was estimated. In addition, the crash characteristics of those crashes that were not avoided by any of the technologies were analysed and compared to all crashes in the database.

Results

Autonomous Emergency Braking (AEB) and Electronic Stability Control (ESC) installed in cars, trucks, and buses were the most effective technologies for reducing MAIS2+ crashes. In particular, crashes between PTWs and passenger cars or heavy vehicles were significantly reduced by an AEB system installed in the cars and heavy vehicles. A pedestrian specific AEB system targeted at reducing car and heavy vehicle collisions with pedestrians was also shown to be effective. Analysing the remaining crashes, it was found that the largest proportion involved PTWs, indicating that car-to-car crashes will not be the most frequent crash type in India in the near future when pre-crash technologies have been widely implemented.

Discussion

Due to the effectiveness of the ESC system, a significant reduction in vehicle loss-of-control crashes will occur when it has been installed in all new passenger cars, heavy vehicles, and

PTWs in India. Although there was a drastic reduction in straight-on-path crashes, they will continue to occur as long as VRUs continue to cross the roads. In fact, this scenario will continue to be the most frequent pre-crash event. The modelled pre-crash safety technologies would prevent some of the serious and fatal crashes involving PTWs. However, single PTW crashes and crashes involving a PTW and a road user other than a passenger car or heavy vehicle would remain, since none of the studied pre-crash safety technologies, except ABS, address these scenarios. Such crashes may be addressed by infrastructure changes focusing on the safety of PTWs. The study also noted that the proportion of PTW user fatalities in India is very high; thus, additional efforts should be made to reduce PTW crashes in India.

Paper II: Estimated Lives Saved by Recently Implemented Vehicle Safety Standards in India: Implications and Future Safety Needs

Introduction

India recently mandated several vehicle safety standards to arrest the trend of increasing road traffic fatalities. Several studies on data from high-income countries have demonstrated that the number of road crashes can be reduced with various countermeasures implemented by road safety policies. The safe system approach, a framework that incorporates safer vehicles, safer roads, and safer speeds, has been proven successful in reducing road traffic fatalities. Even though some of the standards implemented in India have saved lives in other parts of the world for decades, their effect in India may differ, as there are differences in driving behaviour, infrastructure, and the types of vehicles sharing the roads. To the authors' knowledge, no publicly available document explains the rationale for prioritising the recently implemented safety standards in India — separately or in combination. A thorough understanding of future road traffic crashes is required to plan and prioritise the next set of policies targeting the reduction of road traffic fatalities.

Aim

The objective of this study was to estimate the number of lives that will be saved in India by the recently implemented safety standards in India and to characterise future road traffic fatalities.

Method

The study utilised residual crash analysis approach. Explicit deterministic rules were created for each standard, providing two estimates (one conservative and one optimistic) of which types of crash would no longer lead to fatalities. Crash speeds from the literature were used to specify the speed ranges in rules for the crash test regulation rulesets. The rulesets were applied to the historical in-depth crash database Road Accident Sampling System India (RASSI).

Results

The recently implemented regulations are estimated to save 6–13% of road traffic fatalities in India. According to the optimistic estimates, over-speed alerts, offset frontal crash tests, and seatbelt reminders are the three safety standards which are most effective at reducing fatalities. According to the conservative estimates, only the seatbelt reminder had a major positive influence. Extremely high-speed crashes were averted with the optimistic rulesets. The proportion of PTW-user fatalities, already the highest of all participants, will increase further. Hardly any changes in the numbers/proportions of fatalities as a result of fatal crashes involving buses, trucks, and motorised three-wheelers were observed.

Discussion

An overall estimated fatality reduction of 6–13% is far from reaching the target of halving fatalities. The new speed limit warning regulations did not substantially reduce travel speeds,

which cannot be characterised as safe, given the expected fatality outcomes. While progress has been made in protecting the occupants of M1 vehicles (passenger vehicles with not more than eight seats excluding the driver), protection of their crash partners remains rudimentary. Although the pedestrian protection implemented for M1 vehicles does contribute to saving lives, many pedestrian fatalities will remain. Furthermore, the majority of pedestrian fatalities on Indian roads involve, not M1, but other vehicles. Consequently, it does not appear that safety for pedestrians and motorcycle riders will be much improved; these vulnerable road users are expected to account for most fatalities in India in the near future. Improved pedestrian protection for trucks, buses, and PTWs will be necessary to significantly reduce pedestrian fatalities. Our results call for increased attention to fatal crashes involving PTW riders and pedestrians, either through safety standards or other means.

Paper III: Defining crash configurations for Powered Two-Wheelers: Comparing ISO 13232 to recent in-depth crash data from Germany, India, and China

Introduction

The motorcyclist safety standard ISO 13232 is one of the most influential outcomes of past research carried out in Europe and the USA in the field of motorcycle safety. However, the standard has several limitations. First, PTW type, traffic infrastructure, and PTW usage in Europe and the USA are vastly different from those in India, China, and Southeast Asia. Data from India and China did not exist when the ISO 13232 was created in 1996. Further, most studies were carried out on data with a limited sample size. Significant changes in safety regulations and road traffic infrastructure in Europe and the USA have been introduced over the last three decades, which can influence conflicts between road users. The ISO standard does not reflect these changes, since the crash data are now at least 25 years old. Therefore, studies using large samples of crash data from several regions of the world are necessary, to determine representative crash configurations that can be used to update the ISO standard.

Aim

This study aims to first identify the most frequent PTW crash configurations in Germany, India, and China using the most recent information available, and then to compare the configurations with those detailed in the ISO 13232.

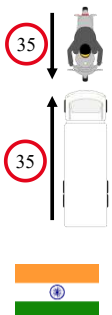
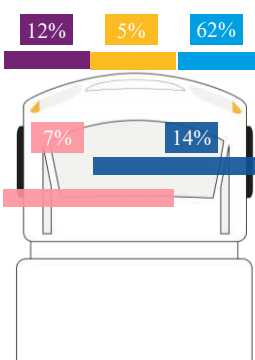
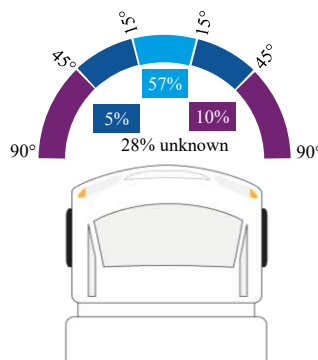

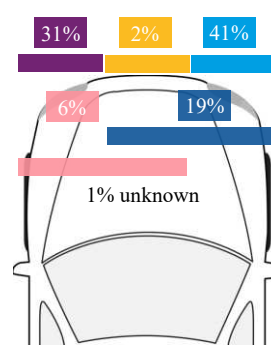
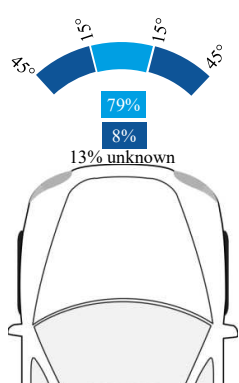
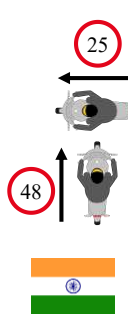
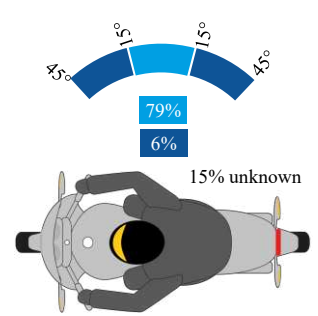
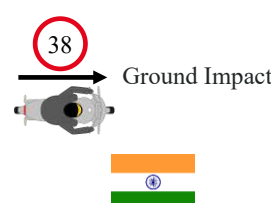
Method

Recent in-depth crash data from Germany, India, and China were used to examine PTW crash configurations in which at least one police-reported serious injury was present and compared the configurations to those in the ISO. After determining which tested crash configurations best reflect the real-world scenarios for each country, we suggested new, more relevant PTW configurations that can guide the development of safety systems to reduce PTW-related fatalities and serious injuries.

Results

Passenger cars were among the top two most frequent collision partners in all three databases. A car front impacting the side of the PTW was the most common configuration shared by the three databases. Trucks were the most common collision partner in India, followed by passenger cars; a rider falling off the PTW, a so-called ground impact or non-collision event, was a common scenario in Germany and India. However, the ISO did not include crash configurations involving trucks or single PTW crashes (either PTW-fixed object collision or PTW non-collision event). Further, in three of the seven ISO crash configurations, one of the collision partners is stationary; however, stationary collision partners were rare in our data.

Table 2. Distribution of impact location and impact angle in the most frequent crash configurations in India - Adapted from (Puthan et al., 2021)

Most Frequent crash configuration	Impact location distribution of the collision partner	Impact angle distributions (relative angle between collision partners)
		
		
	Impact locations not available for PTW	
	Not applicable	Not applicable

Discussion

Our results show that the ISO crash configurations do not represent the most frequent PTW road crashes in any of the countries studied (Germany, India, and China). However, the information in the Chinese database was confined to crashes with a collision partner with four or more wheels, so no ground impacts or PTW-PTW crashes in China were considered; furthermore, weighting factors for these data were not available. For these reasons, the frequency of the Chinese crash configurations across the entire population could not be estimated. However, the observed differences between the three countries imply that a single global standard may not be the best practice. We recommend the use of a mix of crash configurations in future PTW safety performance evaluations: configurations which are frequent all around the world and those which are frequent in the region where the PTW will be marketed. In future, a revised version of the ISO with more relevant crash scenarios could serve as a basis for a full-scale PTW test program.

3. GENERAL DISCUSSION

In this thesis, the effectiveness of pre-crash safety technologies and recently implemented vehicle safety regulations in India were estimated. The first two studies predict that the most important concern in the near future is the high proportion of crashes involving PTWs. The third study provides an understanding of the most frequent PTW crash configurations in India.

This discussion is organised into six parts: thesis scope; the method used to assess the effectiveness of countermeasures; the implications of the results in terms of saving the lives of PTW users and UN SDG targets; limitations of the study; and finally, future work are discussed.

3.1 Scope

The scope is clearly illustrated by the bolded boxes in Table 3 (Table 3). The interventions considered for this thesis, addressed by the three papers, are for the vehicle in the pre-crash and crash phases. A qualitative study on victims in emergency department of a hospital in India identified factors in Haddon Matrix leading to road traffic crashes were over speeding, young age of participants, alcohol intake and fatigue of the driver which is more inclined towards the user (Sharma and Upadhyay, 2020). Another study suggested that India need to work on all the user and infrastructure integrate user behavioural modifications along with vehicle engineering and infrastructural improvements in addition to improved better post-crash care (Rustagi et al., 2018).

Table 3. Adapted from Haddon Matrix (ITF, 2008)

Phase	User (host)	Vehicle (Agent)	Infrastructure (Environment)
Pre-crash (crash prevention)	Attitudes Education Information Impairment Enforcement	Paper I Pre-crash safety technologies Speed Management, (ABS, ESC)	Speed limits Pedestrian facilities Road design and layout
Crash (injury prevention)	Paper-II - (Seatbelt reminder, Alcohol interlock)	Paper-II and Paper III (Offset frontal, side, and pedestrian crash standards, PTW crashworthiness)	Median barriers Crash protective roadside objects
Post-crash (life-sustaining)	First-aid skills Access to medics	Fire risk Ease of access	Congestion Rescue facilities

All the vehicle safety interventions in the matrix that may prevent crashes are mapped to the pre-crash phase of the vehicle, and the standards that may mitigate crashes are mapped to the crash phase of the vehicle. Since the aim was to identify future safety gaps and prevent crashes and casualties, this thesis did not address the post-crash phase. This thesis did not study user behaviour training (such as education and awareness) which can help prevent crashes, either. The thesis did not cover infrastructure improvements or their implications for future road safety.

However, studying the effectiveness of broad infrastructure improvements could be part of future work.

3.2 Effectiveness assessment

In the research for Papers I and II, simple deterministic rules were used to model various countermeasures. The effectiveness of pre-crash safety technologies for improving road safety has been assessed, both retrospectively and prospectively (Alvarez et al., 2017; Bahouth et al., 2017; Kovaceva et al., 2020; Kyriakidis et al., 2015). The prospective studies estimated whether a particular safety intervention would prevent the crash, thereby estimating the intervention's effectiveness before the relevant safety technology was installed in vehicles. These studies used simulator tests or virtual simulations (Sander, 2017) or analysed data from Naturalistic Driving Studies (NDSs). Another method to prospectively assess the effectiveness of a pre-crash technology is to simulate using mathematical model and apply to real-world crash data (Sander, 2017). However, a detailed and validated model which includes crash parameters is required. Evaluating the effectiveness of multiple technologies with detailed simulations would be complex and time-consuming. Moreover, there are other challenges to this approach, like the limited availability of detailed crash parameters and the possibility of multiple technologies that could prevent the same crash. Therefore, for Papers I and II, the effectiveness estimation was carried out using a simplified prospective approach.

The simple deterministic rule-based modelling of safety interventions based on expert judgment is comparatively simple. In fact, it requires fewer crash details than numerical simulation. Although such models are simpler, they are nonetheless useful for understanding the overall effectiveness of individual or combined safety interventions. This type of model makes it possible to avoid double-counting (a fatality prevented twice or more with multiple safety technologies), and future estimates can be made using on certain assumptions. Studies on the effectiveness of several pre-crash safety technologies compared the estimates to estimates from detailed investigations and found that they were comparable (Östling et al., 2019). This approach, modelling safety interventions with simple deterministic rules, was subsequently used to estimate the effectiveness of multiple pre-crash technologies in order to predict future crash rates in Europe and the USA (Lubbe et al., 2018; Ostling et al., 2019; Östling et al., 2019).

Many of the pre-crash safety technologies developed for high-income countries are assumed to be effective in India. This assumption may not be accurate since there are contrasting differences in road infrastructure. This study did not account for scenarios in which drivers ignored a warning or switched off a specific pre-crash safety technology, although these conditions may lead to a crash.

Uncertainties in in-depth crash data are often caused by inaccuracies in the collection parameters. The data are subject to variability, and the sample is of limited size compared to the number of crashes in India. This data uncertainty addressed by bootstrapping, a method to quantify the uncertainty expressed in confidence intervals or variance in the randomly drawn sample estimates (Efron and Tibshirani, 1994). To estimate the uncertainty of sample mean, the data need not be normally distributed even if the sample size is small. This is an advantage over several analytical methods which usually assumes normal distribution of data. Hence bootstrap

simulation a more robust and adaptable method for estimating uncertainty for small sample sizes.

The rule simplification for various safety interventions restricts the model's performance, but it would not be possible to cover all the possibilities. Each technology was modelled with a conservative rule and an optimistic rule to account for modelling uncertainty. The large variations in the optimistic and conservative rules indicate the uncertainty involved.

When the combined effect of multiple safety interventions is estimated, it is possible that more than one technology could address a specific crash—for example, AEB rear-end and seat belt reminder (Elvik Rune, 2009; Strandroth, 2015). In the residual crash approach, a crash is removed if any one of the technologies addresses that crash; hence the crash cannot be double-counted, which is a strength of the study.

The idea that one can predict the crashes that remain after those prevented by technologies have been eliminated is not new. Strandroth et al. devised a new approach to estimating the future impact of vehicle safety technology using assumptions regarding the future implementation of safety technologies (Strandroth et al., 2012). The approach was subsequently further validated (Strandroth, 2015) by predicting the fatalities and injuries of a known period and comparing the predictions to the actual data. This validation method is possible only if historical data is collected and stored accurately. This method can be used to predict future crashes in India as well. However, the method needs to be validated by some when applied to Indian data.

This method has been used in Sweden to predict future crashes in 2030, with a 15-year horizon (Strandroth et al., 2016). However, considering India's slow-paced advancement in road safety in terms of amending regulations and adopting newer vehicle safety standards, the estimates presented in this thesis are expected to be relevant for the next 15 to 20 years. Furthermore, it takes much more time to replace an old vehicle in India than in Sweden, as an official vehicle scrappage policy in India is yet to materialise.

3.3 Result implications

The results of paper I indicate that the pre-crash safety technologies would prevent or mitigate crashes. In fact, if all technologies were installed in the majority of the Indian vehicle fleet, it would prevent about half (58%–65%) of MAIS2+ crashes. However, the proportion of remaining crashes involving PTWs is high, indicating that the presently available pre-crash safety technologies are not capable of preventing such crashes.

As a consequence, saving the lives of PTW users, especially when impacted by heavy vehicles, calls for other strategies to be considered. One possibility is to separate PTW users from the main traffic lane. In the long term, a shift from travelling on PTWs to travelling in cars or to public transport could reduce the number of PTW traffic casualties which is in line with the findings of a regional study in India (Rustagi et al., 2018).

Improving the visibility for truck drivers is a strategy that complements existing technologies. Another countermeasure would improve the protection systems of buses and trucks to prevent under-riding by PTW users. The current under-ride protection system is intended to protect

passenger car occupants who start to slide under a heavy vehicle. In addition, enforcing the proper usage of helmets complements the other safety interventions.

The other notable impact types were PTW-to-PTW and single-PTW crashes. These results imply that India needs to focus on saving the lives of PTW riders. Countermeasures and safety regulations focusing on PTW riders are a must to meet the target of halving road traffic fatalities by 2030. One of the recently mandated vehicle safety standards is ABS for PTWs with engines greater than 125 cm³ and CBS for PTWs with engines less than 125 cm³. These standards are pointing in the right direction. The effectiveness estimates indicate that installing ABS would be beneficial in saving lives, in line with previous studies (Lich et al., 2015; Rizzi et al., 2015). The effectiveness of ESC when installed in passenger cars was 12%–14%, close to a previous research finding of 12% (Moennich et al., 2019). The results of Paper III show that India's most frequent scenario for PTWs was head-on collisions with trucks and cars, followed by non-collision events and PTW-to-PTW crashes. An ISO 13232 tailored to Indian conditions, modified to improve the crashworthiness of PTWs, would be one way forward. Another possible solution would be to install pre-crash safety technologies like AEB or a collision warning system on buses, trucks, and cars. Further, India could also learn from (and adapt) the initiatives on motorcycle safety in Malaysia, which introduced a safety assessment program (Bernama, 2021). Since there are multiple solutions, a detailed cost-benefit analysis for India could be carried to select and implement the best, most cost-effective countermeasure.

The effectiveness of recently mandated vehicle safety standards indicates that these standards help reduce crashes and save lives (6% to 25%) but may fall short of the target of the Stockholm declaration of 50% reduction by 2030. To meet the target, India must consider other interventions, such as improved infrastructure and stricter law enforcements. A combination of several interventions might help India meet the target (Mohan et al., 2021).

The safety standards offer a considerable proportion of their protection to passenger car occupants and less protection to road users outside the vehicle. The pedestrian safety standards for M1 vehicles are a good starting point. However, in India, pedestrians are impacted by heavy vehicles as well: appropriate countermeasures are called for. Examples include improved vehicle frontal structure and an under-ride protection system, implemented in other parts of the world (Transport for London, 2018). Limiting heavy vehicle speeds in areas with many pedestrians and improving the visibility of heavy vehicle drivers would also help reduce such crashes, as would mandating ESC for heavy vehicles and passenger cars.

3.4 Road safety in India and sustainable development

Road transport in India consists of the movement of people and freight. Economic growth and population growth are the two main factors driving the demand for road transport (Transport Research Centre, 2007), which have also increased the demand for road infrastructure. The government is putting effort into expanding infrastructure but is unable to meet the demands created by growth. As a result, India's cities are not pedestrian friendly and reeling with congestion and lack of sufficient parking, which are not consistent with a sustainable development path. The safety interventions that India is implementing should be specifically

tailored to improve India's transportation issues, bringing the country closer to a sustainable future.

The United Nations introduced a framework comprising 17 goals to achieve an improved and sustainable future, known as the UN SDGs. In the framework, the transportation goals have four key attributes: They are equitable, efficient, safe, and green. This thesis contributes to making transportation safer by identifying future gaps in road safety in India.

This thesis describes the remaining crashes, in addition to estimating the number of lives saved. The results can be used by policymakers for future road safety planning and vehicle safety regulations. In this way, the thesis improves road safety by directly contributing to Goal 3 (Ensure healthy lives and promote well-being for all at all ages), Target 3.6 (by 2020, halve the number of global deaths and injuries from road traffic accidents), and Target 11.2 (by 2030, provide access to safe, affordable, accessible, and sustainable transport systems for all). The findings of the first two papers indicate that proportion of VRU fatalities will continue to increase if no actions are taken. Prioritising the safety of VRUs also supports the SDG Target 3.6.

3.5 Limitations

The studies were carried out using an Indian in-depth crash database. To make the data representative of national crash statistics, the weighting factors provided in the database were used. However, the weighting is not entirely accurate, as crashes are under-reported nationwide.

Strandroth estimated injury reduction by applying risk reduction factors identified for each safety intervention to the crash (Strandroth et al., 2016). This thesis did not attempt to quantify the safety benefit of crash mitigation and expected reduction in injury severity. Therefore, the overall potential of these technologies and regulations has been under-estimated since their effects are not just limited to crash prevention but extend to crash mitigation and injury reduction as well.

One of the assumptions made is that 100% of vehicles have all the technologies installed—unlikely, especially since India does not have a strong vehicle scrappage policy. For instance, with voluntary fitment, even after 20 years only 45% of India's passenger car fleet will be fitted with ESC; however, the figure is expected to reach nearly 100% by 2030 (Hynd et al., 2019). Estimates of market penetration for each technology would be beneficial for producing estimates that are closer to reality. However, these estimations would be challenging, due to the complexity involved.

A massive shift in transportation habits, such as car drivers switching to riding buses or bicycles or a completely new transportation mode, is not considered in this thesis. Such a shift would mean that our residual crash analysis results may not give an accurate picture. Even though there are limitations with the method used, it has highlighted some future traffic safety needs, which could be useful for selecting future strategies leading to a safe and sustainable transport system in India.

In addition to vehicle safety regulations and vehicle safety technology implementations, improved infrastructure, and corrective measures in black spots (locations where crashes are frequently occurring) would result in an overall reduction in the number of crashes. The effects of these factors were not directly considered in this thesis, even though they are not entirely independent of the estimates that are presented in this thesis. Given the fact that India's economy will continue to grow in the coming years and major infrastructure reforms are being pushed by the government, road traffic scenarios are expected to change drastically. However, India's history shows that when it comes to executing and implementing various infrastructure initiatives or any reforms in vehicle safety regulations, it is not at the highest pace. As a result, the market penetration of pre-crash technology is expected to grow slowly; the estimates presented in this thesis should be forecast for 15 to 20 years.

3.6 Future Work

The pre-crash safety technology effectiveness estimates in this thesis are based on an ADAS performance regardless of infrastructure design. When these systems are installed in vehicles driven on Indian roads, where road infrastructure is dissimilar that of infrastructures in Europe and in the USA, additional improvements will likely be necessary. The assumption that the ADAS performance will be similar in high-income countries and in India, after some additional improvements to the systems, needs to be validated by detailed simulation of pre-crash technologies such as AEB when installed in vehicles driven on roads in India.

Further, the influence of road infrastructure will have an immediate effect on the safety of the road users and also with the existing vehicle fleet. Therefore, it is worth estimating the impact of various infrastructural improvements on Indian roads.

Lastly, road crashes and casualties are the result of many factors, which can evolve over time. Hence, future work should study the effects of various trends in India, such as economic development, the shift in road users from PTWs to cars or public transportation, and improved enforcement of traffic laws. Their effects need to be studied to prioritise future road safety policies.

4. CONCLUSIONS

This thesis shows that pre-crash safety technologies installed in new vehicles will lead to a reduction of future crashes in India. However, the proportion of heavy vehicles to pedestrians and heavy vehicles to PTW crashes would increase when compared to the present and call for the introduction of additional countermeasures.

Although the recently implemented vehicle safety regulations in India will contribute to substantial fatality reduction, they alone will not achieve the target of 50% reduction in road traffic fatalities that India has committed to by 2030. Our estimates on remaining future crashes indicate that increased attention should be paid to fatal crashes involving PTW riders and collisions with pedestrians, either through the introduction of additional safety standards or introducing infrastructure changes that promote the safety of road users.

I recommend that the safety of PTW users be addressed by focusing on crash protection, in addition to strongly enforcing the helmet law and other existing regulations. It is evident that India needs to improve in all pillars of the safe system approach, namely: safer speeds, safer vehicles, safer roads, and safer road users to substantially reduce road traffic fatalities.

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